Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 129 (2015) 350 – 355

Procedia Engineering

www.elsevier.com/locate/procedia

International Conference on Industrial Engineering

Synthesis of control system for actuators based on shape memory ferromagnetic alloy using inverse problem solution

Bakhvalov Y.A., Grechikhin V.V.* , Kraevskiy I.S.

Platov South-Russian State Polytechnic University (NPI), 132, St. Prosvescheniya, Rostov region, Novocherkassk, 346428, Russian Federation

Abstract

A control system of actuators based on ferromagnetic shape memory alloy is considered. The distinctive feature of the devices is the usage of the distributed magnetizing system and the pulse mode of magnetic reversal. A definition algorithm of ampere-winding of magnetizing system coils with application of the methodology based on the inverse problem solution is developed. A mathematical model of the actuator considering influence of eddy currents and losses of energy on a hysteresis on dynamic processes in active elements is developed. The results of experimental studies are given. The values of ampere-winding in coils and delay time of a magnetic field in pulse control mode of the actuator with active elements from Ni_2MnGa alloy are defined. The offered approaches allow raising the efficiency of the control system of actuators based on ferromagnetic shape memory alloy.

Peer-review under responsibility of the organizing committee of the International Conference on Industrial Engineering (ICIE-2015)

Keywords: actuator, ferromagnetic shape memory alloy, impulse magnetic reversal, inverse problem;

1. Introduction

Development of industrial control systems using intellectual materials in measuring and actuation mechanisms is on the front burner nowadays. Such intellectual material is ferromagnetic shape memory Ni_2MnGa alloys (FSMA), which generate stress and change their geometrical shape in the magnetic field. This distinctive feature allows increasing conversion accuracy, simplifying design of devices, reducing quantity of the components subject to breakage or wear and, as a consequence, increasing efficiency of industrial control systems [1, 2]. Therefore,

* Corresponding author. Tel.: +7-928-600-2864.
E-mail address: vgrech@mail.ru

Peer-review under responsibility of the organizing committee of the International Conference on Industrial Engineering (ICIE-2015)
doi:10.1016/j.proeng.2015.12.076

development of the theory and the principles of creation of the control systems containing actuation and measuring mechanisms on the basis of FSMA is an actual task.

2. Statement of the Problem

The strict requirements are set up in the industrial control systems to actuation mechanisms (actuators). They are to have fast response time, small dimensions and weight. In familiar devices [3-8] the magnetizing system containing coils with the ferromagnetic core is used, that increases their inductance, the reaction time and mass of the device. In the paper [8] the actuator design is offered with two active (subject to deformation) elements from FSMA allowing providing stable position of the drive without continuous consumption of energy. We developed the design which uses positive properties of the specified actuator, but it has the distributed magnetizing system containing *n* pairs of coils without ferromagnetic cores, with pulse magnetic reversal of active elements being applied (Fig. 1) [9]. All the above allows increasing high-speed response, reducing weight and dimensions of the device. Usage of the distributed magnetizing system increases sensitivity and flexibility of control as this provides opportunity to realize the demanded laws of movement of the executive mechanism due to deformation of an active element in the magnetic field, created by separated coils. While in-feeding one couple of coils the length of active element increases by value Δ_m / n , where Δ_m – the maximum increment of the element length at in-feeding of all *n* pairs of coils.

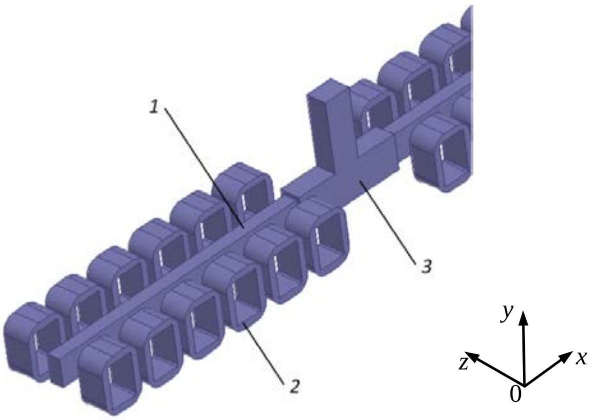

Fig. 1. General view of an actuator with two active elements (*1*), distributed magnetizing coil (*2*) and actuating mechanism (*3*).

The purpose of the present article is to develop a control system of the considered actuator, to define active elements for ampere-windings of coils required for deformation control, and to assess delay time of a magnetic flux in active elements due to eddy currents, magnetic viscosity and hysteresis applying the methodology based on the inverse problem solution. [10]. Devices for program setting for implementation of the demanded law of movement of the executive mechanism and formation of impulses do not differ from the known ones, therefore are not considered in the article [11].

3. Computational algorithm

The algorithm of the inverse problem solution for definition of coils' ampere-windings iw consists in performing the following stages for every $k = 0,1,2,...$:

A. at $iw = iw^{(k)}$ direct problem to be solved: calculation of three-dimensional stationary magnetic field by method of final elements. Internal cycle of specification of magnetic permeability of active element with the use of dependence *B*(*H*) is applied. As a result, $H_{z\min}^{(k)}$ in active element is defined;
B. the value of target function $J^{(k)}\left(iw^{(k)}\right)$ to be calculated and fulfillment of the condition to be checked;

$$J^{(k)}\left(iw^{(k)}\right)=\left(H_{z\min}^{(k)}-H_z^*\right)^2\le\left(\varepsilon H_z^*\right)^2 \tag{1}$$

where ε – set fractional error, H_z^* – z-component of intensity of magnetic field, at which lengthening of active element along axis 0*y* is maximum (Δ_m).

If the condition (1) is satisfied, the external cycle of calculations is completed, the target value of ampere-windings $iw=iw^{(k)}$. If the condition (1) is not satisfied, we pass to the following stage.

C. We minimize the target function by gradient method and define the following approximation

$$iw^{(k+1)}=iw^{(k)}-t^{(k)}\frac{\partial J^{(k)}}{\partial iw}iw^{(k)} \tag{2}$$

where $t^{(k)}$ – step. The derivative in (2) to be defined in number.

D. Coming back to point 1.

For assessment of magnetic flux delay time influencing high-speed response of the device, we transform the Maxwell's system of equations which describes three-dimensional quasistationary electromagnetic field using vector magnetic $\vec{A}$ and scalar electric φ potentials to the view

$$\mathrm{rot}\left(\frac{1}{\mu}\mathrm{rot}\vec{A}\right)+\gamma\left(\frac{\partial\vec{A}}{\partial t}+\mathrm{grad}\varphi\right)=0 \tag{3}$$

$$\mathrm{divgrad}\varphi=0 \tag{4}$$

$$\mathrm{rotrot}\vec{A}=\mu_0\vec{j} \tag{5}$$

$$\mathrm{rotrot}\vec{A}=0 \tag{6}$$

where $\vec{j}$ – current density in coils; γ – electric conductivity, μ – magnetic permeability of ferromagnetic elements; μ_0 – magnetic constant. Equations (3), (4) are valid for ferromagnetics, (5) – for coils, (6) – for other space. The solution of the given equations system with the corresponding boundary and entry conditions is carried out by method of final elements [10].

Not only eddy currents, but also magnetic viscosity and losses of energy on FMSA hysteresis have impact on the dynamic parameters of actuators.

To consider magnetic viscosity the Georgie's equation is added to the system of the equations (3) – (6)

$$T\frac{d\vec{H}}{dt}+\vec{H}=\vec{H}_{st}+\frac{T}{\mu_0}\frac{\partial\vec{B}}{\partial t}\,,\qquad T=\frac{T_0}{1-\left(\left|\vec{B}-\mu_0\left|\vec{H}\right|\right|\big/B_s\right)^2} \tag{7}$$

where B_s – saturation magnetic induction; T_0 – magnetic viscosity constant; $\vec{H}_{st}$ – coercitive force of hysteresis static loop.

To consider losses of energy on a hysteresis Jiles-Atherton model is used. [13, 14]

$$\frac{dM}{dH}=\frac{c}{c+1}\frac{dM_{an}}{dH}+\frac{\tilde{\delta}}{c+1}\frac{M_{an}-M}{k\delta-\alpha\left(M_{an}-M\right)} \tag{8}$$

where M_{an} – unhysteresis magnetization, that is magnetization that would be in case of absence of closing domains wall process; c –elastic displacement constant of ferromagnetic domain borders; k – positive constant of ferromagnetic properties; α – positive constant of magnetic domain coupling,

$$\delta = \mathrm{sign}(dH/dt);\ \tilde{\delta} = \begin{cases} 1, \{dH > 0 \cup M < M_{an}\} \cap \{dH < 0 \cup M > M_{an}\} \\ 0, \{\text{other case}\} \end{cases}$$

The equations (3) – (8) form mathematical model for dynamic parameters study in the devices containing active elements from FMSA.

4. Results and discussion

Experimental studies of the actuator with two active elements (Fig. 1) were carried out to check the offered algorithm and the model developed for control system of the actuator on the basis of active elements. The active elements made from Ni_2MnGa alloy in the form of parallelepipeds with $1 \times 2 \times 20$ mm sizes produced by Adaptamat Inc. were used. [15].

Dependence of $B(H)$ and specific electric conductivity $\gamma = 1.65 \cdot 10^8$ Cm/m of FSMA is considered to be known. It is required to provide $n = 6$ discrete conditions of active elements. Fig. 2 shows the sizes of the magnetizing coils: A = 3 mm; B = 2 mm; C = 0,5 mm; H = 2 mm; L_S = 0,5 mm; R = 0,2 mm.

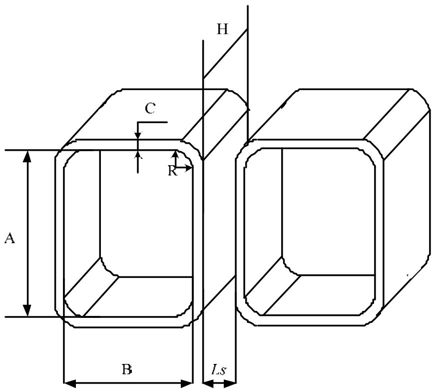

Fig. 2. Form and dimension of a magnetizing coil segment.

It is necessary to define ampere-windings of each coil with which the minimum intensity of a magnetic field in active element meets $H_{z\min} \geq H_z^*$ condition. For the material chosen $H_z^* = 370$ kA/m.

On the basis of scoping calculations $iw^{(0)} = 4000$ A. On the iteration $k = 5$ $iw^{(5)} = 10000$ A is obtained by using algorithm of inverse problem solving for determination of necessary ampere-windings of coils. In this case magnetic field pattern in active element from FSMA takes the following form (Fig. 3). Fig. 4 shows distribution of magnetic field along active element.

Application of model (3) – (9) for determination of dynamic parameters of active elements from FSMA in some cases is complicated due to the lack of data in literature on values of constants (T_0, c, k, etc.) at calculation of influence of viscosity and losses of energy on hysteresis on these parameters. Experimental definition of constants for active elements from alloy Ni_2MnGa is planned in future work [16]. At this stage of the research delay time of magnetic field may be estimated approximately, considering that the energy losses caused by eddy currents make one third of total losses. Then, the total delay of magnetic field is defined by ratio $\tau_\Sigma = 3\tau_{ec}$, where τ_{ec} – the delay caused by action of eddy currents. As shown in [17], for active elements from FSMA $\tau_{ec} = 0.2$ ms. Hence, duration of control impulses is to be more than 0.6 ms.

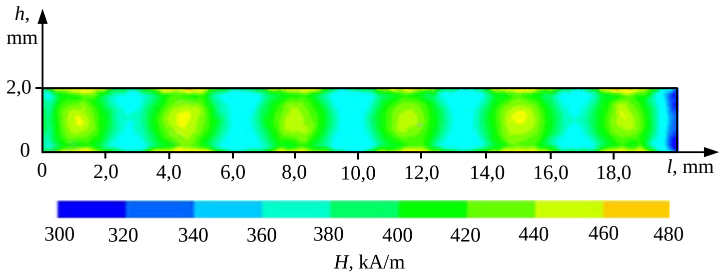

Fig. 3. Pattern of magnetic field in active element from FSMA

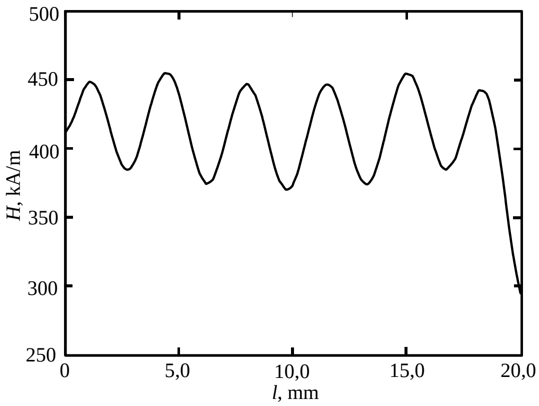

Fig. 4. Distribution of magnetic field along active element

5. Conclusions

Application of active elements from FSMA in actuators of pulse magnetic reversal allows increasing high-speed response, reducing the weight and dimensions of the device. Usage of the distributed magnetizing system increases sensitivity and flexibility of control due to realization of discrete control mode. To choose optimum parameters for control impulses it is rational to use the developed algorithm for coils ampere-windings definition of the magnetizing system with application of the inverse problem solution methodology and the developed mathematical model of the device considering influence of eddy currents, magnetic viscosity and losses of energy on a hysteresis on dynamic processes in active elements. The approaches offered allow solving a problem of efficiency enhancing of synthesis of actuators control on the basis of FSMA.

Acknowledgements

The study results are obtained with the support of the project #1.2690.2014/K "Methods to solve inverse problems of complex system diagnostics (in engineering and healthcare industry) based on full-scale and modeling testing", implemented within the scope of a designing stage for the state-given job.

References

[1] A.N. Vasilev, Ferromagnetics with shape memory effect, Advances in physics. 173 (2003) 577–608.

[2] S.A. Wilson, New materials for micro-scale sensors and actuators: an engineering review, Materials Science & Engineering R-Reports. 56 (2007) 1–129.

[3] I. Suorsa, E. Pagounis, K. Ullakko, Magnetic shape memory actuator performance, Journal of Magnetism and Magnetic Materials. 272 (2004) 2029–2030.

[4] F.-X. Wang, W.-J. Li, Q.-X. Zhang, X.-J. Wu, C. Ge, Design and control of linear actuators made by magnetically controlled shape memory alloy, Proceedings IEEE International Conference on Mechatronics. (2005) 583–586.

[5] E. Asua, J. Feuchtwanger, A. Garcia-Arribas, V. Etxebarria, I. Orue, J.M. Barandiaran, Ferromagnetic shape memory alloy actuator for micro- and nanopositioning, Sensor Letters. 7 (2009) 348–350.

[6] R. Techapiesancharoenkij, J. Simon, D. Bono, S.M. Allen, and R.C. O'Handley, Frequency response of acoustic-assisted Ni–Mn–Ga ferromagnetic-shape-memory-alloy actuator, J.Appl. Phys. 105 (2009) 093923.

[7] L. Riccardi, D. Naso, B. Turchiano, H. Janocha. A precise positioning actuator based on feedback-controlled Magnetic Shape Memory Alloys, Mechatronics. 22 (2012) 568–576.

[8] J. Gauthier, A. Hubert, J. Abadie, C. Lexcellent, Multistable actuator based on magnetic shape memory alloy, Actuator 2006, 10th International Conference on New Actuators, Bremen, Germany. (2006) 787–790.

[9] N.I. Gorbatenko, V.V. Grechikhin, D.V. Shaikhutdinov, Measuring and Actuating Devices Based on Shape Memory Ferromagnets, Metal Science and Heat Treatment. 56 (2015) 609–613.

[10] Yu.A. Bakhvalov, N.I. Gorbatenko, V.V. Grechikhin, Inverse problems in electrical engineering, News of Higher Educational Institutions. Electrical engineering, Novocherkassk, 2014.

[11] Ya.Z. Tsypkin, Foundations of the automatic systems theory, Science, Moscow, 1977.

[12] E.M. Gyorgy, Rotational Model of Flux Reversal in Square Loop Ferrites, J. Appl. Phys. 28 (1957) 1011.

[13] D.C. Jiles, D.L. Atherton,Theory of Ferromagnetic Hysteresis, Journal of Magnetism and Magnetic Materials. 61 (1986) 48–60.

[14] D.C. Jiles, J.B.Thoelke, Theory of ferromagnetic hysteresis: determination of Model parameters from Experimental hysteresis loops, IEEE Transactions on Magnetics. 25 (1989) 3928–3930.

[15] Information on http://www.adaptamat.com.

[16] N.I. Gorbatenko, Full-scale and model experiments of pieces made from ferromagnetic materials, SKNZ VSH, Rostov on Don, 2001.

[17] V.V. Grechikhin, A.V. Kudrya, N.A. Kudrya. Estimation of eddy current influence on high-speed response of actuators on the basis of shape memory material, News of Higher Educational Institutions. North Caucasian region. Engineering sciences. 6 (2014) 33–35.